TESTING AND MODELING OF SOIL - NAILED SLOPES

Synopsis submitted in fulfillment of the requirements for the Degree of

DOCTOR OF PHILOSOPHY

By

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April, 2017

ABSTRACT

Soil nailing is a technique to facilitate the stabilization of an existing or a newly constructed excavation/slope. With the development in field of infrastructure, transportation and other man – made structures, available land has become scarce. Hence, the urge of utilizing weak and unstable ground is inevitable. Accordingly, numerous methods have been developed in the past with soil nailing being one such solution to counter this problem. Moreover, development of remote hilly areas, construction through difficult terrains and uninterrupted communication between far off places, all require stabilization of ground conditions. Keeping this view in mind, soil nailing method has been considered as a cost effective and reliable method of ground stabilization.

The present research work is an investigation in understanding soil nailing mechanism in slopes with different types of soil nails against the conventional soil nails that have been used in the past. To achieve that three different types of soil nail have been fabricated namely smooth soil nail, screw soil nail and helical soil nail. To comprehend the response of slopes towards reinforcement due to soil nails, 36 small - scale laboratory testing of soil – nailed slopes has been conducted. The soil slopes are constructed at three different slope angles of 45°, 60° and vertical cut of 90° with horizontal. Each type of 6 soil nails are used to reinforce the soil slope at four different nail inclinations of 0°, 15°, 20° and 30° with horizontal. Thus, effect of slope angle and nail inclination on soil nailing mechanism is studied. The optimum inclination of soil nail to the corresponding slope is angle determined. The variation in soil nailing mechanism with change in nail type from conventional smooth nail to screw nail and similarly to helical nail is also examined. This enable to assess the behavior of soil slopes to change in nail geometry and nail installation method. A gradual increasing surcharge load is also applied at slope crest to study the load – deformation of soil – nailed slopes in comparison to unreinforced soil slopes for all slope angles.

The failure mechanism, failure surface and nail forces generated along nail length during slope failure are also determined from model testing. To validate the model testing, numerical modeling has been carried out using Limit Equilibrium Method and Finite Element method. The Limit Equilibrium Analysis has been done using sub – routine Slope/W and Finite Element Analysis is carried out by Plaxis 2D code. The numerical modeling with both these methods has been done for all slope angle of 45°, 60° and 90° with nail inclinations of 0°, 15°, 20° and 30° for smooth, screw and helical nails. The factor of safety, slope deformation with surcharge loading, soil – nailed slope failure mechanism, failure slip surfaces and nail forces along nail length are predicted. A comparative study is also carried out between results

obtained from model testing and numerical modeling of soil – nailed slopes. The pullout behavior of helical soil nail has also been investigated through two - dimensional and three – dimensional finite element analysis. Plaxis 2D has been used for two - dimensional analysis and Abaqus/Explicit is used for three – dimensional analysis. The pullout mechanism of helical soil nail has been optimized by studying variations of non - dimensional factors with different combination helical plate spacing, helical plate diameter, embedment ratios, anchorage length ratios and number of helical plates. The validation of results of model testing, numerical modeling of soil – nailed slopes and helical nail pullout behavior is also done by published results from literature.

The model testing results have revealed an increase in load carrying capacity of reinforced slopes as compared to unreinforced slopes. The maximum load carrying capacity is obtained for slope angle of 45° with nail inclination of 15°. However, nail inclined at 0° is found to give best results for 90° vertical cut. It is found that load carrying capacity of slopes is not increased beyond nail inclinations of 15°. It is also depicted that helical nails provide the best reinforcement followed by screw nails and then smooth nails. The slope crest is observed to undergo settlement with outward horizontal slope movement under gradual increasing surcharge load. The failure slip surface as given by model testing accounts for a circular slip surface for 45° and 60° slope and complex unpredictable slip surface for 90° vertical cut. However, for 90° slope, the slip surface is characterized by overturning of slope about its toe for all nail inclinations. The nail forces are found maximum at intermediate nail length and approaching zero at nail end. These observations are similar for all different types of soil nails used.

Results from numerical modeling further validate the results of model testing with maximum factor of safety greater than 2 obtained for helical nails. The predicted slip surfaces, slope deformations and nail forces are similar to model testing with slight variations. The numerical modeling of pullout of helical nail presents that failure mechanism can be well predicted by both two dimensional and three – dimensional finite element analysis. However, variation in magnitude is observed in pullout capacity from both analyses. There lies a critical relative helical plate spacing, diameter and number of plates beyond which failure mechanism shows transition between deep global to shallow local failure.

Keywords: *soil nails, model testing, limit equilibrium method, finite element method, pullout behavior*

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1. INTRODUCTION

1.1 **General**

Large scale construction work such as housing projects, extensive expansion of road networks and other man - made activities such as deforestation have resulted in disturbing the fragile eco – system. This exploitation of natural ground conditions renders instability and leads to hazards such as landslides. An unstable slope always creates difficulties not only in development of that area but also poses threat to human life. For example, creating an uninterrupted communication between far off areas requires the expansion of roads, which in turn depends on the excavation and construction through weak and unstable grounds. Similarly, ever increasing population has created scarcity of land. Since infrastructural development signifies the development of nation, construction of buildings never ceases to grow. To meet this never ending demand for buildings and road networks, stabilization of unstable ground conditions serves as the best suited remedial measure. Development of hilly and remote areas, construction of dams and hydropower projects on difficult terrains, utilization of weak ground conditions and even increasing defense of the country all require stabilization of unstable ground conditions in some way or the other. Many stabilization techniques have been developed in the past to combat these situations. Ground stabilization techniques like mechanical and chemical ground stabilization, grouting, earth retaining structures, anchors and soil nailing have all proved beneficial in providing structural and serviceable stability. The present research work focuses on one such ground improvement technique for unstable slopes called as soil nailing.

1.2 **Soil Nailing Technique through Ages**

The method of stabilizing excavations by in – situ reinforcement dated way back to 1959, which involved installation of steel reinforcement without pretension in rock followed by application of reinforced shotcrete. Without the prestress condition, combination of passive steel reinforcement with shotcrete developed its strength by mobilization of tensile strength of steel reinforcement at relatively small deformations in

the surrounding ground. This combination of passive reinforcement and shotcrete when applied to soil was termed as soil nailing.

Soil nailing evolved as an efficient technique in the form of a rock bolting system of underground excavation referred to as the New Austrian Tunneling Method in 1960 (Rabcewicz, 1964). Initially, utilized at stabilization of hard rock excavations, soil nailing technique proved to be successful even in less competent soil conditions of silt, sand and gravel. The viability of this technique in diverse soil conditions lead to its widespread use in West Germany (Stocker et al., 1979; Gassler and Gudehus, 1981), France (Plumelle, 1986; Clouterre, 1991), North America (Shen et al., 1981), USA (Elias and Juran, 1991; FHWA, 1994), UK (Jewell and Pedley, 1992), Brazil (Ortigao et al., 1995), Japan (Hirano 2001), Australia (Seto et al. 1992) and Hong Kong (Watkins and Powell,1992; GEO, 2008). In India, soil nailing technique is also rapidly increasing with Indian Institute of Science, Bangalore and Indian Road Congress (IRC) working together to form its design guidelines (Babu and Singh, 2009).

1.3 **Mechanism of Soil Nail in Soil – Nailed Structures**

Soil is a material which is weak in tension. Addition of a material having significant tensile strength not only increases the tensile strength of soil but also provides it stability against shear strength failures. In order to achieve that closely spaced passive inclusions in the form of steel bars or rods are inserted into soil mass. The failure of slopes is generally a shear failure occurring at a potential slip surface which divides the soil mass into two states (Schlosser, 1982). The soil mass infront of the failure surface tends to move outwards and is in an active state of earth pressure. The soil mass behind the failure surface is subjected to passive earth pressure condition. The reasons for soil nail to be referred as ‘passive inclusions’ depends on the fact that soil nails are not pre - tensioned like anchors and have a length such that it extends deep into the passive zone of soil mass. The passive inclusion now acts as a tie fastening the active and passive soil mass during failure. The outward movement of soil mass during failure induces tensile forces in the soil domain which are resisted by these inclusions called soil nails. Thus soil nails are subjected to tensile forces during slope failure. The tensile strength of soil nails is thus mobilized due to outward movement of soil mass. Consequently, soil nails are under a constant pullout which is resisted by nail length in

passive soil zone and is termed as soil nail pullout resistance. Moreover, to further restrain the slope and nail movement, soil - nailed structures are provided with a permanent or temporary facing panel. This facing also helps resist the tensile forces of soil mass and provides an additional tensile resistance to soil nails. Hence, during failure of soil – nailed structures, the forces mobilized along the soil nail length are nail tensile capacity, nail pullout capacity and facing capacity (FHWA, 2003). Moreover, it has also been found by researchers in the past that though soil nails work predominantly in tension, but shear and bending stresses are also mobilized at the intersection of the slip surface and soil nails (Juran, 1985; Jewell and Pedley, 1990 and 1992; Bridle and Davies, 1997). However, the contribution of shear and bending is considered negligible under service load condition (Jewell and Pedley, 1992, FHWA 2003).

The potential failure modes for a soil – nailed system can be classified as external failure mode, internal failure mode and facing failure mode. The occurrence of these failure modes governs the limiting conditions for soil – nailed slopes. If a soil – nail system collapses under induced stresses from surcharge which is greater than the soil shear strength, then it refers to strength limit state. A service limit state is one in which soil – nailed wall deforms excessively hampering safe and normal operation of structure. For optimum design of a soil – nail structure, the above mentioned limit states must be satisfied, hence safety check against three different failure modes becomes necessary. The external failure mode is concerned with the condition that potential failure surface may or may not intersect the soil nails. In such a case the soil mass undergoes a block failure and will result in global stability failure, sliding failure and base failure. The load transfer mechanism between soil nail and surrounding soil determines the internal failure mode of soil – nailed structure. As the reinforced system deforms, bond strength between soil nail embedded grout column and surrounding soil is mobilized progressively along grout - surrounding soil interface. The tensile forces are thus mobilized and bond stresses are distributed along the soil nail length. The distribution of bond stress and tensile strength of soil nail governs the internal failure modes of system. Internal failure modes of soil – nailed system includes nail pullout failure, tensile failure of nail, bending and shear of nails and slippage of nail – grout interface. The facing

failure mode is related to flexure failure, punching shear failure and headed – stud tensile failure of connection between nail head and facing.

The external and internal stability of a soil – nailed system can be evaluated using limit equilibrium method (LEM). The limit equilibrium method is based on the concept of finding the most critical surface along which the destabilizing forces causes failure. Other factors on which the external stability analysis depends are the structure height, nail lengths and the soil type of nailed system. The external stability analysis is used to find the critical factor of safety by considering a number of failure surfaces such as planar, bi – linear, circular, parabolic and log – spiral. Since the analysis involves large error and trial data, computer programs like SNAIL and SLOPE/W are commonly used. However, finite element method (FEM) based computer programmes are also employed for external and internal stability analysis of soil – nailed slopes. PLAXIS 2D and FLAC 2D has always been common choices for finite element analysis of soil nail structures. The advantage of studying non – linear stress strain behavior of soil during failure and load - deformation of reinforced slope failure are well predicted by finite element method. LEM uses different slip circles and predicts slip circle with minimum factor of safety as critical. The convergence of force equilibrium and moment equilibrium governs the FOS and hence critical slip surface. Moreover, the local factor of safety is constant throughout the analysis in LEM, thus eliminating the cases of local slip failure. On the other hand, the slip surface obtained from FEM is based on stress distribution within the continuum. The stress distribution in more realistic in FEM as local factor of safety is not constant and thus convergence of results is achieved (Rawat and Gupta 2016).

1.4 **Concept of Soil – Nail interaction**

The soil – nail interaction plays an important role in load transfer mechanism of a soil – nailed system. The tensile forces developed in nails are result of frictional forces due to soil – nail interaction. This interaction reduces the imposed shear force in soil by increasing the normal stresses in soil along potential failure surface, thus allowing higher shear resistance to be mobilised by the bearing soil. The soil mass above the nail act as an overburden and in addition to surcharge it increases the normal stress on the nail (Luo, 2000). The outward movement of soil mass is also a consequence of soil mass

loading. The outward movement causes a pull on the anchorage length of the nail i.e. nail length behind the failure surface. Alternatively, pullout resistance of nail is mobilized by apparent coefficient of friction at soil – nail interface which is a function of the normal stress around the nail. The tensile forces are mobilized by axial stress, whereas lateral strains mobilize shear and bending forces in the soil nail. The soil - nail interaction is influenced by factors such as nail stiffness, nail inclination, nail bending strength, soil stiffness and soil shear strength. The nail thus resists the soil deformation by its mobilized tensile capacity, pullout capacity, shear stress at soil nail interface and facing capacity. The facing capacity is generally a fraction of ultimate nail capacity and is primarily caused due to nail and facing interaction. The nail force is found to vary from zero at the nail end to a maximum value at intermediate length and a reduced value at slope/wall facing. However, maximum tensile capacity does not necessarily occur at nail - slip surface intersection. The distribution of shear stress along nail length is not uniform but changes from positive to negative at the intersection of nail and failure surface. Due to improper soil – nail interaction, significant reduction in radial stresses during nail installation around the drill hole is also observed due to a phenomenon known as soil arching. However, pressure grouting is usually employed to counter this reduction in radial stress. Moreover, a soil – nailed system develops a significant portion of bond resistance from drill hole roughness and soil grout interlocking (Tokhi, 2016).

1.5 **Types of soil nails**

Based on their installation method, conventional soil nails can be categorized in various types as driven nails, launched nails, self drilling/jet grouted nails and grouted nails. With recent development in field of soil nailing, researchers are working in order to easy the installation process of soil nails such that less disturbances are caused to surrounding soil and fewer spoils are produced with increased surface roughness to develop necessary bond strength instead of grouting the soil nail. Tokhi, 2016 developed a screw nail with helical plates near the nail tip so that it can be easily installed by providing torque at its head. A similar attempt has also been made by Chan and Rehman, 2017 by using a screw – in soil nail for slope reinforcement. Stephens et al., 2013 developed a groutless spiralnail with helical ribs along the nail length for soil reinforcement.

1.6 Review of Literature

In order to study the behaviour of soil nailing for soil reinforcement, researchers have carried out both small scale laboratory testing and large scale field testing. To understand the failure mechanism of reinforced slopes, model tests were conducted by Stocker et al., 1979; Gassler and Gudeus, 1981 from which it was concluded that reinforced slopes undergo a two wedge failure surface. Similar observation was also made by Ramstad et al., 1978. Kitamura et al., 1988 studied orientation of nails from model testing, likewise Jewell, 1990 investigated internal stability of soil - nailed system. Gutierrez and tatsuoka, 1988; Hayashi et al.,1990; Drabkin et al., 1995; Kodaka et al., 1995; Mittal, 2006; Gosavi et al., 2009; Zhang et al., 2014; Rawat et al., 2014; Chan and Raman, 2017 were among other researchers to study soil – nailed structures through small scale model testing. The actual repsonse of reinforcing action of soil nails, horizontal wall displacements, stress – strain behviour of soil can best be comprehended through large scale field study. Such field studies has been carried out by Schlosser et al., 1992; Murthy et al., 2002; Turner et al., 2005; Prashant and Mukherjee, 2010; Lindsay et al., 2015 and Stephens et al., 2015. As discussed in section 1.4, it is observed that soil – nail interaction governs the reinforcing action of nails during soil failure. Under the light of this concept, extensive testing, numerical modelling and theoretical analysis has been carried out to understand the soil – structure interaction through small and large direct shear tests (Jewell, 1980; Ingold, 1982; Pedley, 1990; Tei, 1993; Milligan and Tei, 1998), interface shear tests (Assadi, 1975; Johston and Romstad, 1989, Morris, 1999) pullout test of soil nail with various parameters such as overburden pressure, soil dilation, soil saturation, grouting pressure and nail roughness (Chang et al., 1977; Cartier and Gigan, 1983; Palmeira and Milligan, 1989; Chang and Milligan 1996; Franzen, 1998; Lee et al., 2001; Hong et al., 2003; Chu, 2003; Chu and Yin, 2005; Junaideen et al. 2004; Pradhan et al., 2006; Lum, 2007; Gosavi et al., 2008; Tan et al., 2008; Yin et al. 2009; Babu and Singh, 2010; Zhou et al., 2011; Hong et al., 2013). Pullout studies have also been conducted on innovative nail types such as glass fibre – reinforced polymer soil nails by Zhu et al., 2011 and Zhang 2014, groutless spiralnail by Stephens et al. 2013, moso bamboo soil nails by Dai et al., 2015 and screw nails by Tokhi, 2016.

The stress – strain behviour of a soil – nailed system has always been a complex phenomena. Non – linear stress around soil nails, plastic strain generation during slope deformation, complex failure surfaces during slope failure and nail forces developed along nail length have imposed difficulties in completely relying on field and model testing results to properly interpret the performance of soil nails in context of reinforcement. For a better insight numerical modelling of reinforced soil slopes and structures is achieved by FEM and LEM based software codes (Wright and Duncan, 1991; Zhang et al., 1999; Yang and Drumm, 2000; Ng and Lee, 2002; Cai and Ugai, 2003; Patra and Basudhar, 2004; Ann et al., 2004; Fan and Luo, 2007; Zhou et al., 2009; Chin et al., 2010; Jaya and Annie, 2011; Rotte et al., 2011; Lin et al., 2013; Gao, 2016). The summary of literature review reflects that soil – nailed model tests have depicted similar responses to field slopes with variations in magnitude. Large scale field test reflects the exact behaviour of soil nails due to effect of installation processes, which are not taken into accountduring model testing and difference between in - situ and model testing boundary conditions. Numerical modelling by either LEM or 2-D FEM can be utilized to predict the safety factors and deformations of actual soil – nailed structures with fair bit of accuracy. It also enables to understand the failure mechanism by deducing the soil stress – strain variations and shear stress variations along soil nail length. However, researchers are still trying to develop soil nails with less installation difficulties so that in – situ soil properties are not altered significantly. Similarly, a gap still prevails in search of a type of nail which can develop significant interaction with surrounding soil and be installed without drill hole and grouting.

1.7 **Objectives of the Research**

Based on literature review and research gaps, following objectives of the research are determined:

1) To study the behaviour of soil – nailed slopes at different slope angles and nail inclinations using smooth, screw and helical soil nails by model testing.
2) To investigate the load – deformation behaviour, failure mechanism and nail forces developed along nail length in reinforced slopes during model testing.
3) To develop numerical models of different reinforced slopes with smooth, screw and helical nails using limit equilibrium analysis and finite element analysis.

4) To study and optimize the pullout behaviour of helical soil nail using two – dimesional and three – dimesional finite element analysis.
5) To carry out comparison and validation of model testing and numerical modelling results.

1.8 **Organisation of the thesis**

The first chapter of the thesis provides a brief introduction to the use of soil nailing, concept of soil – nail interaction and evolution of soil nailing technique with time.

The second chapter deals with the review of available literature on small scale laboratory model testing and large scale field testing. It also gives insight on previous experimental, theoretical and analytical studies conducted to understand the soil – nail interaction mechanism. The chapter also outlines the objectives of the present research work.

The third chapter deals with testing of materials used and model testing of unreinforced and reinforced slopes by smooth nails different slope angles (β) of 30º, 45º and 60º and nail inclinations (i) of 0°, 15°, 20° and 30° with smooth, screw and helical soil nails.

The fourth chapter presents complete numerical modeling procedure adopted for simulation of different reinforced slopes using different types of soil nails. It also provides the numerical modeling of helical soil nail pullout for various combinations of helical plate spacing, diameter and number of helical plates.

The fifth chapter includes all the results obtained from material testing, model testing and numerical modeling using limit equilibrium and finite element analysis. Comparison and discussions regarding the critical observations from results between model testing and numerical modeling are also presented here, This chapter also provides validation of model testing and numerical modeling from past literature.

The sixth chapter deals with the conclusions derived from model testing and numerical modeling of different soil – nailed slopes.

2. METHODOLOGY

2.1 General

The chapter outlines the methodology adopted to achieve the objectives of present research work. A brief description of material testing, model testing and soil nail fabrication is provided. The numerical modeling of various soil – nailed slopes using limit equilibrium and finite element analysis is also incorporated in this chapter.

2.2.1 Backfill Material

The backfill material used for slope construction is collected from Nalagarh, District Solan (Himachal Pradesh). Preliminary tests of soil identification are carried out in the laboratory to determine the backfill properties. The specific gravity of fill material is determined from pyconometer test, sieve analysis was carried out for soil classification and shear strength parameters were determined from direct shear test. From these tests, it was concluded that the soil used in slope construction is a poorly graded sand soil (SP) with specific gravity of 2.68. A moisture content of 18% is added to poorly graded sand in order to facilitate the construction of 45°, 60° and 90° slopes. The moisture content of 18% is optimum moisture content obtained from proctor test which corresponds to a maximum dry unit weight of 13.98 kN/m^3. The shear strength parameters of fill material are determined by direct shear tests under consolidated drained (CD) conditions with 18% moisture content, which yields a cohesion value of 10.41 kN/m^2 and angle of internal friction as 30.79°. All the parameters of fill material are given in Table 1.

Table 1. Properties of fill material

Properties	Values (Units)
Specific Gravity (G)	2.68
Soil type	Poorly Graded Sand (SP)
Moisture content (w)	18%
Cohesion (c)	10.41 kN/m^2
Angle of internal friction (ϕ)	30.79°
Maximum dry unit weight (γ_d)	13.98 kN/m^3
Initial void ratio (e_0)	0.88

2.2.2 Material for smooth, screw and helical soil nails

The smooth nails used in model testing are fabricated from hollow aluminium tubes having diameter of 15 mm and 150 mm of length. A constant length of nails has

been used throughout the model testing. Similarly for fabrication of screw nails and helical nails, mild steel bars having a diameter of 16 mm is used. The steel bar is worked upon by a thread rolling machine which renders its surface with threads of height 0.15 mm. Thus, the fabricated screw nail has major diameter (D) of 16 mm and minor diameter of 15.7 mm. The end of screw nail, about 20 mm in length is made tapered to ease the initial penetration in soil slope. The helical nails are made by welding three helical plates of diameter 45 mm at 40 mm spacing. Tensile strength test is carried out to obtain modulus of elasticity for smooth nails as 69 GPa whereas for screw and helical nails, modulus of elasticity of 200 GPa is obtained.

2.3 Model preparation and nail installation

A rectangular 60 cm (length) x 40 (width) cm x 60 (height) cm model tank is fabricated using Perspex sheets of thickness 12 mm. The Perspex sheets are fastened to the iron angles by bolts. The sides of the tank are braced by iron strips to restrain the lateral deformation of sheets during testing. The tank was filled with sand obtained locally for construction of slopes at desired slope angles. The construction of soil slopes is carried out by rainfall technique to attain a specified unit weight (γ) = 16.5 kN/m^3 for both the slopes. This unit weight corresponds to a relative density of 70%. The step – wise procedure for construction of slopes with β = 45°, 60° and 90° are as follows: (1) A temporary plywood slope facing is fixed at the desired inclination inside the model tank. To ensure correct slope inclination, markings are made on the perspex sheet. (2) With the plywood facing intact, the sand is filled in model tank with rainfall technique. The first layer is the base layer with a height of 10 cm. (3) At regular intervals, red colour dye tracer powder is used. It enables the observer to physically study deformation of soil layers during loading by its altered pattern. (4) Above the base layer with tracer, next soil layer is constructed as mentioned above. (5) The process is repeated till the desired height of 30 cm of slope is achieved. (6) The finished slope with model box is weighed and volume of soil used in construction of slopes is calculated. The nails are installed at predetermined inclination of i = 0°, 15°, 20° and 30° with the horizontal using a protactor. The smooth nails are inserted into specified positions through the circular opening created in the temporaray facing. On the other hand, screw nails and helical nails are installed by applying torque manually at nail head. The nails are screwed - in through

the holes in slope facing in rectangular pattern with equal horizontal spacing and different vertical spacing corresponding to slanting height of slopes. A total of six smooth nails, screw nails and helical nails are installed in a pattern of three rows and two columns. Moreover, care is taken to ensure that the influence area for each nail i.e. S_h x S_v is less than or equal to 4 m^2 as recommended by FHWA, 2003.

2.4 Model testing procedure

The completed reinforced slope models at different slope angles and nail inclinations are loaded with a gradual increasing surcharge load at slope crest. The loading of modelled reinforced slopes is carried out in Universal Testing Machine (UTM) available at Geotechnical laboratory in Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh. Servo hydraulic UTM with a load frame capacity of 2000 kN is used to apply an increasing surcharge load on the crest of soil slopes. The continuous application of the surcharge load is simulated by applying the load at a rate of 10 N/s.

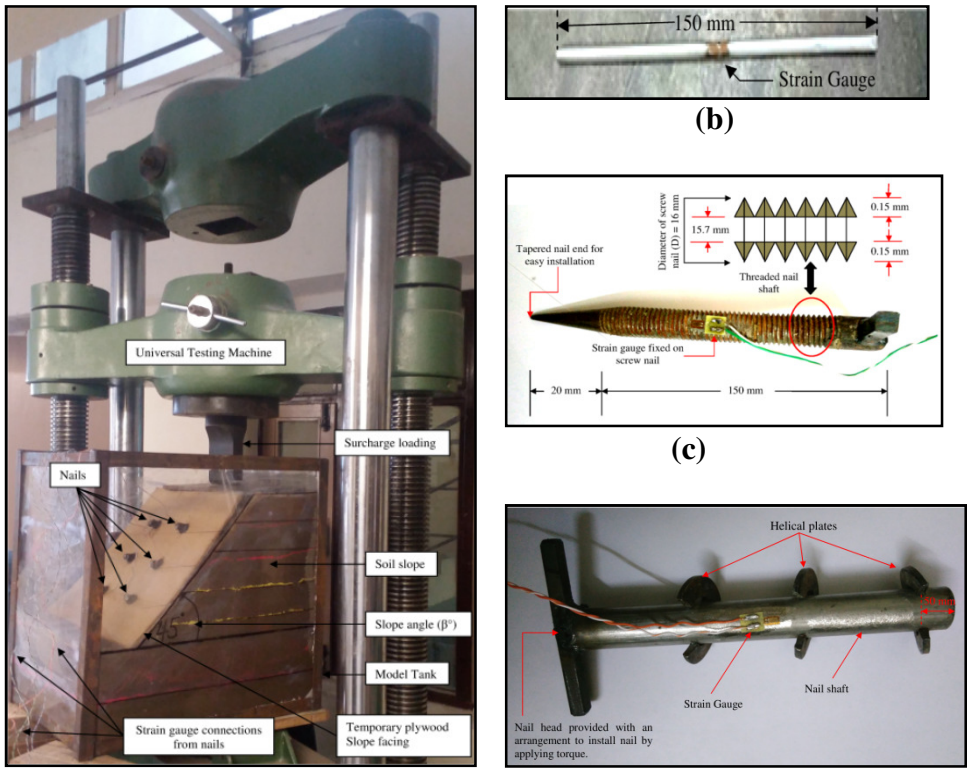


Fig. 2.1(a) The complete soil – nailed slope model with three different types of soil nails used (b) smooth nail (c) screw nail (d) helical nail

To ensure uniform distribution of load on slope crest, a steel plate with a plan area of 20 cm x 40 cm and thickness 4 mm is placed on the slope crest. The thickness of iron plate for uniform distribution on slope crest is selected after repeated trials with iron plates of thickness 2 mm and 3 mm. Thus, uniform distribution of load on slope crest was ensured. Each smooth, screw and helical soil nail is attached with a strain gauge of type BKCT-3 (resistance 119.2± 0.2 ohms, gage factor: 1.92± 2% and gage length 3 mm) to measure the nail strains. The strain gauge values are read off from multimeters connected to individual strain gauge in terms of resistance, which are converted to strain values. The complete soil – nailed slope model along with the three different types of soil nails used is shown in Fig. 2.1. The model testing is used to investigate the failure mechanism of reinforced slopes, potential failure surfaces, load – deformation behavior and nail forces developed during slope movement along the nail length.

2.5 Numerical modeling of soil – nailed slopes

2.5.1 With smooth nails

Numerical modeling of soil slopes with smooth nail is carried out by using a finite element analysis code Plaxis 2D. The non – linear stress strain behavior of soil during failure of soil – nail system is found to be accurately predicted by finite element analysis. The soil domain is simulated using a Mohr – Coulomb model for slope angles 45º, 60º and 90° with and without smooth nail condition at different nail inclinations of 0°, 15°, 20°and 30°for each slope angle. The failure pattern, deformed mesh, the load - settlement curves for unreinforced and reinforced slopes, the nail forces for different soil nail inclinations is obtained from the FEM analysis. The modeling and analysis is carried out by simulating a non-linear and time-dependent behavior of soil with similar geometry of slope as used in model testing. Identical boundary conditions to model testing are simulated by using a fixed base of model in x, y and z directions. The sides of model are allowed displacement in vertical direction, whereas both horizontal and vertical displacements are considered free along the slope length.

The smooth soil nails are simulated using elasto – plastic plate elements with specified axial and bending stiffness as obtained from material testing of nails. These nails are converted to equivalent circular sections of 15 mm diameter by using formulation as given in literature. For simulation of soil – nail interaction, an interface is

defined along the nail length in terms of a roughness factor (R_{inter}) (Brinkgreve, 2002). The value of this roughness factor reflects the interface friction between the nail and surrounding soil. To obtain coefficient of interface friction value, direct shear test is conducted with and without nail condition. The coefficient of friction obtained from direct shear tests is converted to apparent coefficient of interface friction by formulation. This interface friction value is thus used as R_{inter}. The roughness factor used for smooth nails is 0.25. Modelling of gradual increasing surcharge load is carried out by applying a uniformly distributed load on slope crest of magnitude equal to the maximum load at failure obtained from model testing. In this manner a load – control simulation is achieved. The properties of soil domain and simulated nail are same as that used in model testing. For developing more accurate soil – nail interaction, 2-D meshing is made finer along the nail length. The finite element analysis is carried out using strength reduction method (SRM) to obtain factor of safety for each reinforced slope and plain – strain analysis method to study the slope failure under surcharge loading.

Along with finite element analysis of reinforced soil slopes, limit equilibrium analysis is also carried out using Slope/W which is a sub-routine of software package Geoslope. The limit equilibrium analysis enables to locate the most critical slip surface during failure. In Slope/W, modelling of soil mass is done using Mohr – Coulomb soil model with similar boundary conditions as used in finite element analysis. However, Slope/W incorporates soil nail into analysis in form of a concentrated loads which reduce the destabilizing forces in soil slopes (Slope/W manual, 2001). Soil nails are simulated in terms of pullout load which incorporates the nail roughness in terms of interface friction is calculated theoretically by formulations in literature. The analysis of reinforced models is done by Morgenstern – Price method, which uses a relation between interslice shear forces and inters slice normal forces. The interslice function selected in the analysis is a half – sine function with a constant factor of safety distribution calculation. Thus, factor of safety corresponding to the most critical failure surface is obtained.

2.5.2 With screw nails

Numerical modelling with of reinforced slopes with screw nails is also carried out both by LEM and FEM using the same tools of Slope/W and Plaxis 2D, respectively. The modelling procedure for soil domain and nail elements remain the same as done in

reinforced slopes with smooth nails. However, the only difference in soil – nail interaction between smooth and screw nails is the mobilized coefficient of interface friction mobilized due to rough surface of screw nails. To incorporate this effect, study of interface friction between screw nail surface and soil is conducted by employing direct shear test. The coefficient of friction obtained from direct shear test is used to calculate the coefficient of interface friction theoretically from relations between coefficient of friction (ϕ) from direct shear test and coefficient of interface friction (f^*) from pullout test. This interface friction value accounts for surface roughness of screw nails and is incorporated in numerical modelling as R_{inter}= 1 (i.e. very rough) in Plaxis 2D and f^* = 0.766 to obtain pullout load in Slope/W.

2.5.3 With Helical nails

In the absence of literature on pullout of helical nails, coefficient of interface friction between helical soil nail and surrounding soil cannot be predicted by the available equations for smooth nails in literature. Hence to understand the soil – helical nail interaction, finite element analysis of helical nail pullout behavior is carried out. To simplify the problem, initially uniform stress condition around helical soil nail is considered. This enables it to be treated as a 2-D axisymmetric problem. The horizontal orientation of helical soil nails is simulated by applying horizontal load on the absorbent boundary to account for overburden acting, when nail is pulled out horizontally. The constitutive soil modelling is carried out using a hardening soil model with fixed top and bottom boundary condition in the vertical direction. The left boundary condition is fixed in horizontal direction and displacement is allowed from right boundary for application of overburden. In this analysis, due to restriction on simulation of helical pitch, helical plates are taken circular discs with zero pitch. The nail shaft and helical plates are modelled using an elastic – plastic, 15 – noded plate elements. Other nail parameters are similar to those used for smooth and screw nails. The interface stiffness between soil and nail is handled by a virtual thickness '$t_{interface}$' which is automatically generated by FE subroutine. The R_{inter} value used for current analysis is 0.67, which is used when no previous data is available for soil structure interaction. A small pull out force (Q_0 = 10 kN) is applied on the nail head to initialize the pull out. A detailed investigation of

variation in helical soil nail failure mechanism and pullout capacity with number and spacing of helical plates, varying diameter of helical plates is studied.

The helical nail configurations in the FE analysis is altered by using different diameters of helical plates (D_h) with a constant shaft (D_s) diameter of 19 mm. The D_h/D_s ratio used are 1.4, 2.4, 3.4 and 4.4. The helical plate diameter used in the study are 26.6, 45.6, 64.6 and 83.6 mm. Throughout all the analysis, the bottom helix is fixed at a distance of 15 mm from the nail tip. By varying the number of helical plates between 1 to 3, three different types of helical nails such as single helical soil nail (1 - H), double helical soil nail (2 - H) and multi – helical soil nail (3 - H) are studied. The variation in pullout capacity, failure responses and break – out factors with change in helical plate spacing, helical plate diameter, embedment ratio (H/D_h) and number of helical plates is studied. Moreover, tapered helical nail is also simulated by varying the diameter of top, middle and bottom helical plates with different D_h/D_s ratios.

In order to achieve more realistic simulation of pullout of helical nails, 3 - D finite element analysis of helical nails is also carried out using Abaqus/Explicit sub – routine. The soil domain and helical nail is simulated as deformable solid elements. An 8 - noded linear brick element with reduced integration (C3D8R) is used to model the soil domain. The soil elasticity is adopted from model testing whereas a Drucker – Prager/Cap model is used to simulate the soil plasticity. The properties of nail remain the same as in model testing. Due to complexities involved in meshing, helical plates are considered to be circular plates with zero pitch. The shaft and circular disc simulation consisted of 1200 and 216 linear hexahedral elements, respectively of type similar to soil continuum defined as C3D8R of first – order. The discs and nail shaft interaction is defined by a surface to surface 'tie' constraint, which permits the same degree of freedom as that of nail shaft (Hibbit et al., 2013). The simulated nail with circular disc is accommodated in a sandy soil domain by assigning a 'penalty – type' contact between surrounding soil and simulated nail. The pullout of helical soil nail is carried out by a load – control method with a maximum pull of 30 kN acting at the nail head. The load is applied in a series of steps.

The boundary conditions are identical to an actual pullout of soil nail with all sides fixed in x, y and z directions. An overburden is also applied on the top surface of

the box which is allowed displacement in vertical direction and a circular opening at the nail head is created by allowing horizontal displacement of helical nail as it is pullout during testing. The analysis is done to study the variation in pullout capacity, bearing capacity and normalized pullout load (P/P_0) with variation in relative circular plate spacing ratio (s/D_c), diameter ratio (d_s/D_c), length ratio (L/D_c), displacement ratio (u/L) and number of circular plates. Using a similar modeling procedure, analysis of reinforced slopes using helical nails is also carried in Abaqus/Explicit for the optimized helical soil nail configuration. For helical nails, LE analysis is not carried out due to the limitation of simulation of helical soil nail geometry and load transfer mechanism of helical nail which is not only dependent on shaft friction but bearing by helical plates as well.

3. RESULTS AND DISCUSSION

3.1 General

This chapter provides some significant results obtained from model testing. The critical observations from numerical modeling of reinforced soil slope model tests are also included. Comparison between results from model testing with different types of soil nails and its validation by numerical analysis is given in this chapter. A brief discussion on the results obtained and comparison with published results from literature has been done.

3.2 Results from Model Testing

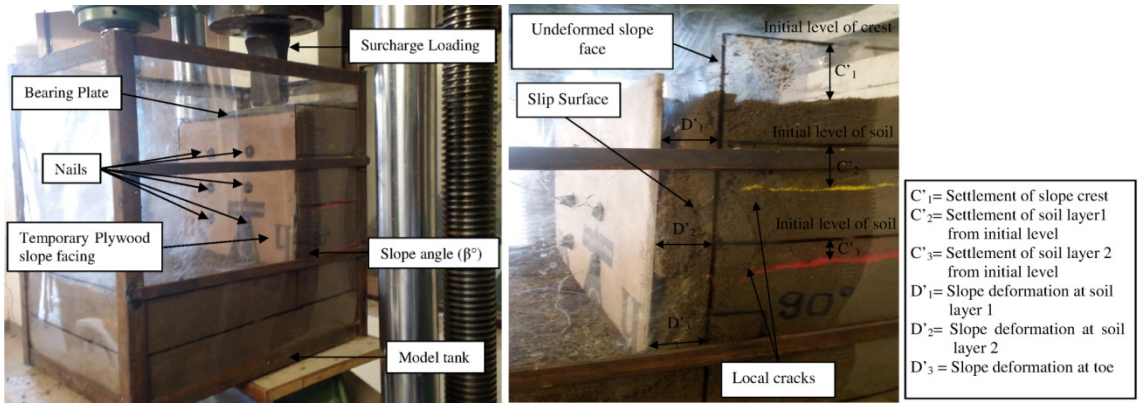
The model testing results obtained for reinforced slopes with smooth nails at 45° depicts a load carrying capacity of 19.4 kN for a slope settlement of 11.7 mm. Similarly for 60° and 90°, the load carrying capacity of slopes is 17.3 kN and 15427.3 kN, respectively. However, slope settlement of 10.6 mm and 9.6 mm are obtained for 60° and 90° slopes. All the maximum load carrying capacities of slope are found for nail inclination of 0°. In comparison to reinforced slopes, the unreinforced slopes reflect much smaller slope capacity for almost similar slope settlement. For unreinforced slopes of 45°, 60° and 90°, load capacities as obtained from model testing are 13.2 kN, 11.6 kN and 10.2 kN, respectively for slope settlement of 9.4 mm, 11.3 mm and 13.5 mm, respectively.

The slopes reinforced by using screw nails shows an increase in the load bearing capacity of slopes for all three slope angles of 45°, 60° and 90°. The load bearing capacity of 41 kN with settlement of 125 mm for $\beta = 45°$, 35.2 kN with settlement of 94.85 mm for $\beta = 60°$ and 30.2 kN with settlement of 71.98 mm for $\beta = 90°$ is obtained for reinforced with screw nails. However, the maximum load carrying capacity with screw nails is obtained with $\theta = 15°$ for both $\beta = 45°$ and 60°, whereas for $\beta = 90°$, $\theta = 0°$ to the horizontal gives the maximum load carrying capacity. The reason for this variation can be accounted for angle at which failure surface intersects the soil nails. The failure surface intersecting nails at right angles is found to depict significant

reinforcing action to slope deformation. For β = 90° with θ = 0°, the slip surface is expected to have intersected the top row of nails at right angles.

For helical nail reinforced soil slopes, similar variation in results are obtained. The maximum load is obtained for β = 45° followed by β = 60° and 90°. However an increase in load carrying capacity is observed for reinforced slopes with helical nails as compared to screw nails. The effect of nail inclination (θ) on the load carrying capacity of slopes is similar to screw nails with maximum reinforcing action of helical nails obtained at θ = 15° for β = 45° and 60°. For β = 90°, the most effective nail inclination is at θ = 0°. Such variations for different slope angles and nail inclinations have also been observed by researchers like Mittal, 2006; Fan and Luo, 2007.

The failure surface from model testing depicted that for smooth and screw soil nails can be classified as a circular slip surface for 45° and 60° slope angles. However, for β = 90°, shape of the failure surface is difficult to be categorized. The failure surface for β = 90° though have a common feature of rotation of slope face about the toe. Based on this observation, slip surface for 90° slope angle is classified as a log – spiral slip surface. The failure surface for screw nailed soil slope of 90° obtained from model testing is shown in Fig. 3.1.



(a) **(b)**

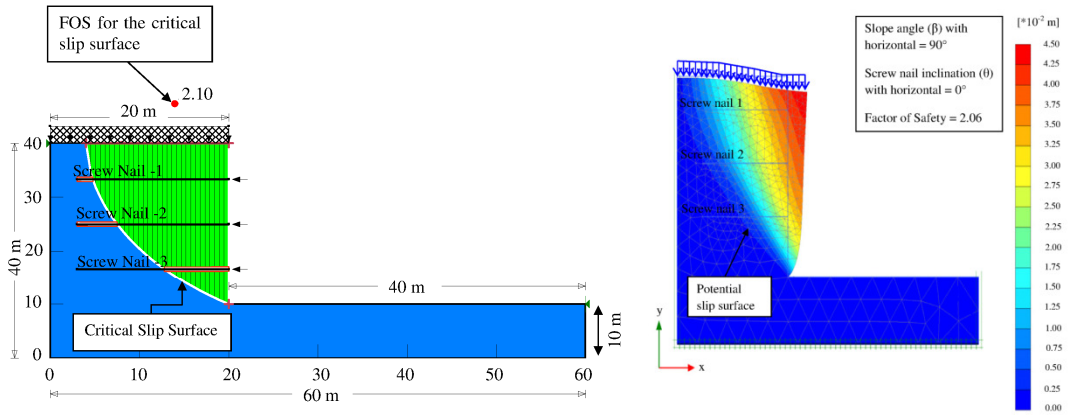
Fig. 3.1 Screw nailed soil slope with β = 90° (a) before testing (b) after testing

The nail forces along nail length obtained from model testing shows that maximum nail forces are obtained for nail inclinations yielding maximum load carrying capacity. For smooth, screw and helical nails, the nail forces are found to follow a non – linear pattern. The nail forces in the bottom nails are found to be greater than middle and top nails. The nail forces depict an

increase with nail length to a maximum value and then decrease to zero at the nail end. Such pattern of nail axial forces are common for smooth, screw and helical nails.

3.2 Results from Numerical modeling of soil - nailed slopes

It is observed that the factor of safety (FOS) calculated from the limit equilibrium method for soil - nailed slopes with smooth nails is found to be 1.82 for β = 45° with i = 15°. Similarly β = 60°, the highest factor of safety of 1.53 is found for nail inclination of 15°. The factor of safety for β = 90° is found to be 1.51 i = 0°. Similarly for soil – nailed slopes with screw nails factor of safety of 2.43, 2.22 and 2.10 is obtained for β = 45°, β = 60° and β = 90° with i = 0°. Similarly, factor of safety are also obtained from finite element analysis. The failure surfaces obtained from LE analysis and FE analysis are shown in Fig. 3.2 for screw nailed soil slopes of 90° with i = 0°.

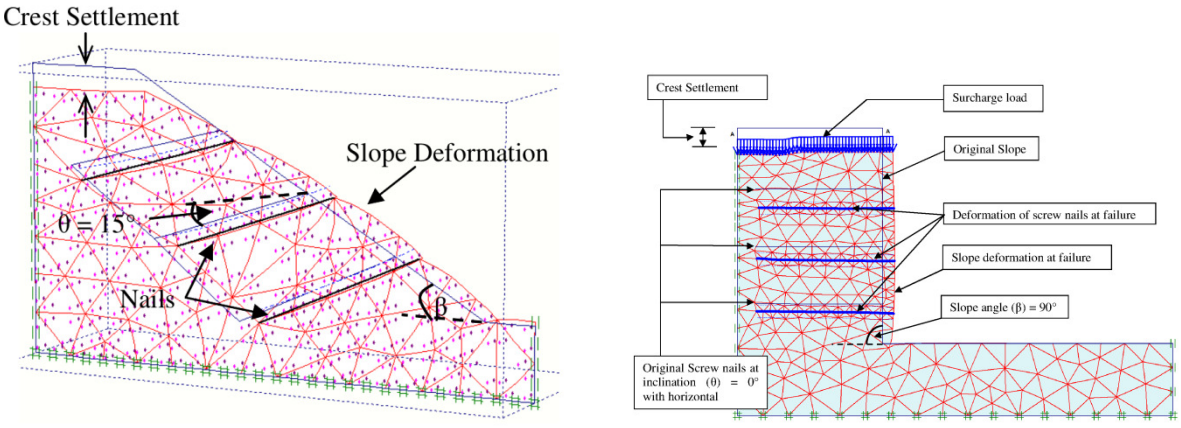


(a) **(b)**

Fig. 3.2 Failure surface and FOS for screw nailed soil slope from (a) Slope/W (b) Plaxis 2D

The deformed soil – nailed slopes as obtained from numerical modelling by finite element analysis in Plaxis 2D is shown in Fig. 4.3. It is evident that deformation of reinforced soil slopes is characterized by settlement of crest and simultaneously bulging of slope during failure. As the crest settles under gradually increasing surcharge load, the soil gets compressed. This effect of increasing surcharge is transferred to the top screw nail. In addition to the overburden, an additional surcharge is now being beared by the top nail. Simultaneously, the strain values are increasing due to increase in stress. This leads to the formation of plastic strain zones in reinforced slopes. If these plastic strain zones lie within the reinforced slope mass, the

deformations are small and within limit. These deformation characteristics are a necessary for assessing the serviceability of screw nailed soil slope system.



(a) **(b)**

Fig 3.3 Deformation of reinforced soil slope from finite element analysis (a) β = 45°, *i* = 15° (b) β = 90°, *i* = 0°

The load – deformation behaviour of smooth nail reinforced slope is observed to give higher load carrying capacity and smaller settlement as compared to model testing (Fig. 3.4).

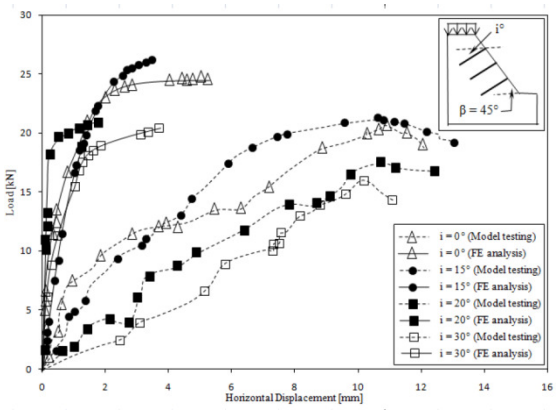

Load [kN]
Horizontal Displacement [mm]
i°
β = 45°
i = 0° (Model testing)
i = 0° (FE analysis)
i = 15° (Model testing)
i = 15° (FE analysis)
i = 20° (Model testing)
i = 20° (FE analysis)
i = 30° (Model testing)
i = 30° (FE analysis)

Fig. 3.4 Load – deformation of soil – nailed slope with smooth nails for β = 45° from model testing and finite element analysis (Plaxis 2D)

However, for screw nailed soil slopes finite element analysis yields a lower load bearing capacity and settlement than model testing (Fig. 3.5). The reason for this variation can be the difference in installation processes between smooth nail and screw nail. During the installation of smooth nails, the in situ soil conditions are disturbed which decrease the shear strength of soil.

Hence during failure, shear stress mobilized at smooth nail – soil interface are small. Since numerical modelling of smooth nails does not incorporate the installation process, the interface friction mobilized is high and thus large load carrying capacity is observed.

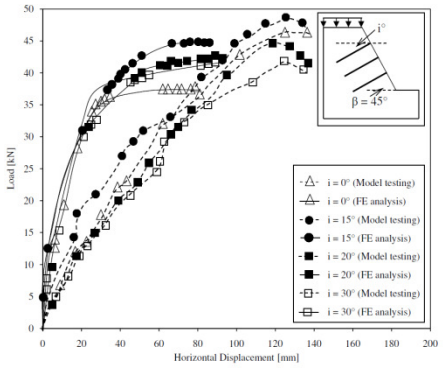
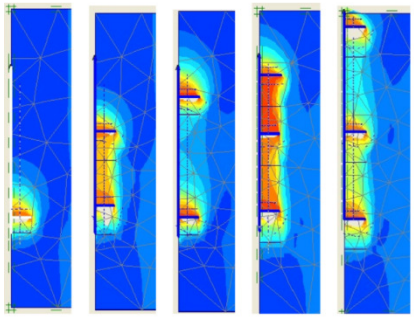

Load [kN]
Horizontal Displacement [mm]
i°
β = 45°
i = 0° (Model testing)
i = 0° (FE analysis)
i = 15° (Model testing)
i = 15° (FE analysis)
i = 20° (Model testing)
i = 20° (FE analysis)
i = 30° (Model testing)
i = 30° (FE analysis)

Fig. 3.5 Load – deformation of soil – nailed slope with screw nails for β = 45° from model testing and finite element analysis (Plaxis 2D)

In case of screw nails, the torque provided for nail installation causes minimal disturbance to surrounding soil. Moreover, due to high roughness of screw nails better interlocking is developed between the teeth of screw nails and soil particles. When screw nails are modelled, the interface is simulated by using an increased interface friction value without modelling the actual installation torque. This difference is testing and modelling can be accounted for less load carrying capacity of screw nailed soil slopes obtained from finite element analysis.



(a) (b) (c) (d) (e)

Fig. 3.6 Variation in failure mechanism with different spacing of helical plates (a)1-H (b) 2-H at s/D_h = 1.5 (c) 2-H at s/D_h = 3.5 (d) 3-H at s/D_h = 1.5 (e) 3-H at s/D_h = 3.5

It is observed from 2 – D finite element analysis of pullout behaviour of helical soil nails that maximum pullout force of 635.6 kN is obtained for $s/D_h > 3$ and $D_h/D_s = 4.4$ with nail having three helical plates. Similarly, as shown in Fig. 3.6, the failure mechanism is found to change from deep global cylindrical failure to shallow local individual plate failure as the spacing between the plates is varied.

As observed from Fig. 3.7 it can be stated that beyond a critical H/D_h ratio, the breakout factor follows a non – linear pattern which is due to the change in failure mechanism from deep global to shallow local failure during pullout of helical nails.

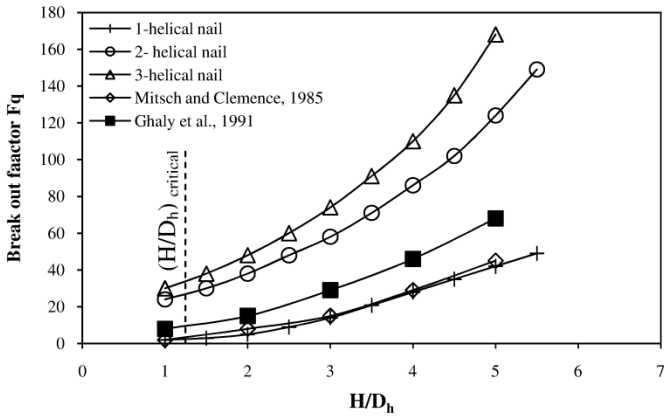


Fig. 3.7 Breakout factor variation with embedment ratio (H/D_h)

A variation is pullout capacity of helical nails is observed by 3 – D finite element analysis using Abaqus/Explicit code. However, only change in magnitude of pullout capacity and corresponding nail displacement is observed. From 3-D FE analysis it is found that peak pullout load is achieved for nail with four circular discs having a maximum load capacity of 20.34 kN for nail displacement of 27.12 mm. Moreover, pullout - displacement curves follow a 'zip – zap' unsmooth curve as compared to pullout – displacement curves obtained from Plaxis 2D. This 'zip – zap' nature of the curves can be accounted for shear stress softening around nail during pullout. Similar observations has been reported in past by Hong et al., 2003.

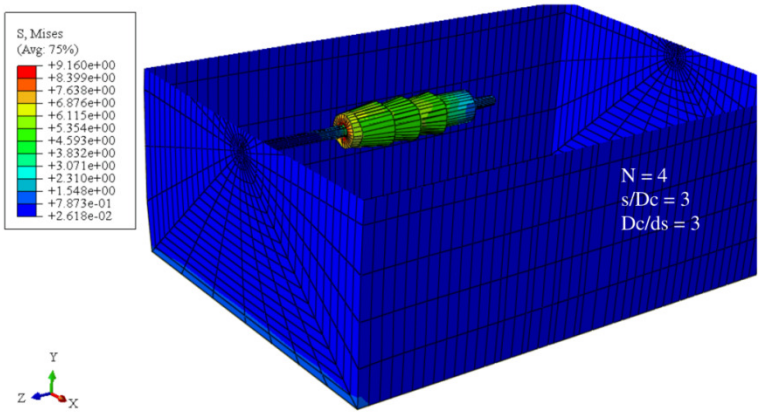


Fig. 3.8 Stress contours during pullout of soil nail with four circular discs

The stress in soil during load transfer mechanism as observed from 3 – D finite element analysis is shown in Fig. 3.8. The maximum pullout capacity 20.34 kN is obtained for $s/D_c = 3$ and $D_c/d_s = 3$ for nail with four circular discs. The failure surface, load – deformation characteristics and nail forces for soil - nailed slopes with helical nails are similar to screw nails with variation in magnitude.

4. CONCLUSIONS

4.1 General

The chapter enlists the conclusions derived from the results of model testing and numerical modeling of soil – nailed slopes with three different types of soil nails. It also incorporates some major conclusions based on comparison of results between model testing and numerical modeling.

4.2 Conclusions

Based on the results obtained from model testing of soil – nailed slopes with smooth soil nails, screw soil nails, helical soil nails and numerical modeling of these reinforced slopes, the following conclusions can be made:

1) The load carrying capacity of an unreinforced can be increased by reinforcing the slope with nails. The soil – nailed slopes undergo smaller slope deformation as compared to unreinforced slopes. The reinforcing action of helical nails and screw nails is greater than smooth nails depicted by maximum load carrying capacity for helical nails followed by screw nails and then smooth nails. However, it can also be concluded that slope deformation does not follow the same effect of reinforcement corresponding to these three types of nails.
2) The maximum load carrying capacity varies with slope angle (β) and nail inclination (θ). For $\beta \leq 60°$, optimum nail inclination is $\theta = 15°$. For $\beta > 60°$, $\theta = 0°$ gives the maximum load carrying capacity. Thus, it can be concluded that maximum reinforcing action of soil nails can be obtained d between $\theta = 0°$ to $15°$ and beyond $\theta = 15°$, the effect of soil nailing on soil slopes with increasing slope angels from $\beta = 45°$ to $90°$ is minimal. This pattern of soil nail reinforcement is common for all types of nails namely smooth, screw and helical soil nails.
3) The failure surface for a soil –nailed slope can be inferred as a circular slip failure for $\beta \leq 60°$ irrespective of the type of nail used for reinforcement. For $\beta = 90°$, slip surface is much complex to predict but is characterized by overturning of slope about the toe for all

nail types. Moreover, soil – nailed failure mechanism will always include settlement of slope crest under surcharge loads and horizontal displacements of slope face for all nail types.

4) Limit equilibrium method and Finite element method can well predict the soil – nailed slope response. The critical slip surfaces obtained from LEM are similar to model testing whereas slope deformation behavior of soil – nailed slopes during failure are close to model testing as depicted by FEM.
5) The factor of safety more than 1.5 for all nail types depicts that soil nailing of unreinforced slope provides stability against failure. However, better stability is obtained by using helical nails as compared to screw nails and smooth nails.
6) The load transfer mechanism of helical nails is different from that of screw nails and smooth nails. Helical nails derive its pullout resistance capacity from nail shaft friction and additional bearing from helical plates, whereas screw nails and smooth nails primarily depend upon interface friction between nail surface and surround soil to generate pullout resistance during failure.
7) The helical plate spacing, diameter, embedment ratio, length ratio and number of helical plates all affect the pullout capacity of helical soil nails. There is a critical s/D_h or s/D_c ratio of 3 and D_h/D_s or D_c/d_s ratio of 3 beyond which load transfer mechanism of helical soil nails changes from deep global cylindrical failure to shallow local individual plate failure.
8) The helical nails and screw nails more suitable than smooth nails as they provide ease of installation with minimum spoils and disturbance to surrounding soil. They also provide satisfactory performance in reinforcement of unstable slopes.

Scope for Future Work

The present research work has been limited to static analysis of soil – nailed slopes which leaves a research gap for dynamic analysis of soil slopes using smooth, screw and helical nails. Moreover, soil nailing has been carried out in same soil conditions of drained sandy soil has been used for all model testing and numerical modeling which can be further looked into by using a different type of soil such as cohesive soil or a $c - \phi$ soil. Further validation of this research work can be done by carrying out large scale field studies using similar types of soil nails as smooth, screw and helical.

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6. LIST OF PUBLICATIONS

6.1 Journal Publications

[1] Rawat, S., and Gupta, A. K. (2016). "An Experimental and Analytical Study of Slope Stability by Soil Nailing" *Electronic Journal of Geotechnical Engineering*, 21(17), 5577-5597. **[Scopus Indexed]**

[2] Rawat, S., and Gupta, A. K. (2016). "Analysis of a Nailed Soil Slope Using Limit Equilibrium and Finite Element Methods." *International Journal of Geosynthetics and Ground Engineering*, *2*(4), 34. **[Springer]**

[3] Rawat, S., and Gupta, A. K. (2017). "Numerical Modelling of Pullout of Helical Soil – Nail." *Journal of Rock Mechanics and Geotechnical Engineering*. **(Accepted) [Scopus Indexed]**

[4] Rawat, S., and Gupta, A. K. (2017). "Testing and Modelling of Screw Nailed Soil Slopes." *Indian Geotechnical Journal*, 1-20. **[Scopus Indexed]**

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